Development and performance evaluation of a standing-wave thermo-acoustic engine

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***Abstract* — The current work describes the development, construction and experimental investigation of a simple Standing-Wave Thermo-Acoustic Engine (SWTAE). This work aims at providing additional clarity on the construction and the performance of simple SWTAEs. The proposed SWTAE will be used to drive a traveling wave thermo-acoustic refrigerator, through the generated sound wave and ultimately induce cooling. For experimental purposes, the heat supply used in this experimental study are electric cartridge heaters. This study provides clarity as far as the temperature supplied to the system is concerned. To characterize the acoustic power of the SWTAE, the onset temperature differences across the stack for the engine to start producing sound has been measured. Three different configurations have been investigated and general trends showing the relationship between the supply heat, the generated sound wave and the minimum temperature required to produce a sound wave have been obtained.**

Keywords— *Standing-wave, Thermo-acoustic engine, sound, design.*

I. INTRODUCTION

Thermo-acoustic technology has become an interesting engineering research area over the last three decades [1]. It involves the conversion of acoustic energy into thermal energy or the reverse process of converting thermal energy into sound, thus inducing cooling [2]. Thermo-acoustic is a branch of science that deals with the relation between thermodynamics and acoustics for the energy conversion between heat and sound. This energy conversion is clean because it uses a benign gas as a working fluid. In a thermo-acoustic engine, the energy conversion is between the consumption of heat energy to produce sound energy. In a thermo-acoustic refrigerator, a sound is used to induce cooling. In both these devices, the energy conversion takes place within the stack through a thermo-acoustic effect. Defined by Lord Rayleigh in 1878, a thermo-acoustic effect is the vibration that is encouraged when heat is given to air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction [3]. The thermo-acoustic effect within the stack results in a generation of sound in thermo-acoustic engine and induction of cooling in thermo-acoustic refrigerator. A typical cycle showing thermo-acoustic effect within a stack is shown in Fig. 1. During the expansion, heat is given to air at the time of greatest condensation. During compression, Heat is taken from air at the time of greatest rarefaction.

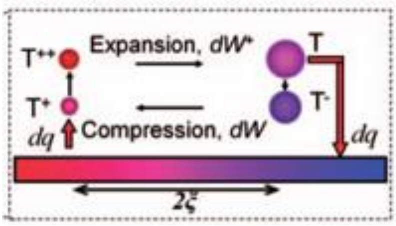

Fig. 1. Illustration of thermo-acoustic effect within simple thermo-acoustic refrigerator (Adapted from Ref. [3])

A thermo-acoustic engine comprises of the stack and two heat exchangers that sandwich the stack. One heat exchanger is a hot heat exchanger (HHX) and the other is a cold heat exchanger (CHX) also known as the Ambient Heat Exchanger (AHX). Heat is supplied to the hot heat exchanger while cooling the cold heat exchanger. Upon reaching the suitable onset temperature difference across the stack, a sound is generated. A description of typical components of a simple standing-wave thermo-acoustic engine is shown in Fig. 2. T_H and T_c are the Hot and Cold temperature thermocouples, respectively. For experimental purposes, electrical cartridge heaters are generally considered in order to generate the heat required by the engine.

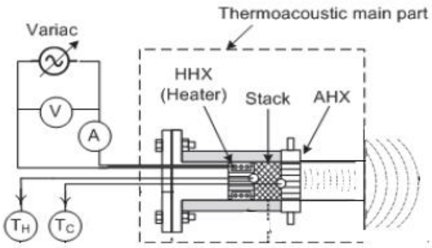

Fig. 2: Schematic drawing of a Thermo-acoustic Engine (Adapted from reference [4])

A SWTAE is a straight hollow medium with one end closed and one end opened. The system setup compels the cycle of the produced sound wave to be a standing wave. The wave produced within the working medium is a standing wave because it is a combination of two waves moving in opposite directions. Each wave has the same amplitude and frequency, thus superimposing on each other to add or cancel each other's energies [5].

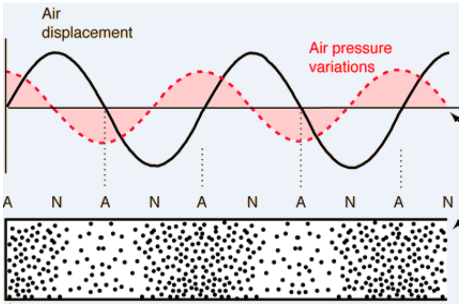

Fig. 3. Schematic presentation of a standing wave (Adapted from reference [5])

The development of a standing wave within a hollow medium, with a benign gas as a working fluid, encompasses reflections from both the open end and the closed end. The closed end is the pressure anti-node (velocity or displacement node), and the open end is the velocity or displacement anti-node (pressure node) [5]. This meaning that, because the air on the closed end bounces from the closed end, this results to the air not moving out of a system and hence pressure anti-node, and the open end allowing motion of the air hence velocity anti-node. The current work aims to exploit these positive attributes, and maximize the sound produced by the SWTAE to feed into a travelling wave thermo-acoustic refrigerator to induce cooling and assess the potential of cooling as shown in Fig. 4.

Thermo-acoustic engines convert heat energy into high amplitude sound waves. The high amplitude waves can be used in the field of cryogenics, electricity generation and refrigeration. Also from the environmental point of view, that the working fluids used in this technology are nonpolluting [6]. Previous research studies [1] point out the effect of the onset temperature, the geometrical configuration of the device and the pressure amplitude within the device on its performance, with the main objective being to analyze the performance of a thermo-acoustic prime mover to be used at the latter stage as main sound generator for a travelling-wave thermo-acoustic refrigerator.

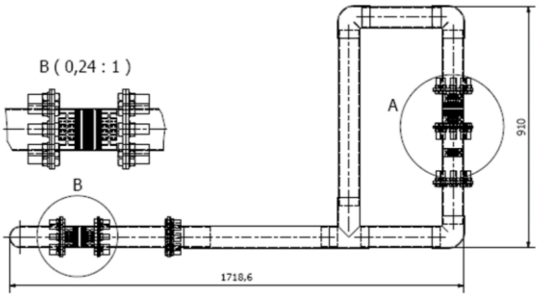

Fig. 4. Travelling-wave thermoacoustic refrigerator (A) driven by a SWTAE (B)

A study was done on a hot air driven thermo-acoustic engine. The study investigated the potential of producing sound waves intense enough to drive a thermo-acoustic refrigerator in order to induce cooling to the required temperature [7]. Hot air is used to drive the thermo-acoustic stirling engine to resemble the real world application. The engine produces 300W of acoustic power, with a performance of 41% Carnot efficiency at a hot air temperature of 620ºC. It is reported that the hot heat exchanger can be improved for optimum hot heat exchange on the face of the stack [7].

An experimental investigation whose objective was to look into the Impact of Ceramic Substrates Geometry on the Performance of Simple Thermo-Acoustic Engines was done [8]. The study reveals that the acoustic power is directly proportional to the sound pressure level. Furthermore, in order to achieve higher acoustic power, the stack has to be large, the pores size wider and the stack should be positioned closer to the closed end. The viscous resistance could be minimized if the stack is relatively short, the pores size larger with the stack positioned closer to the closed end. The convective heat flux could be minimized if the stack is relatively short, the pores size smaller with the stack positioned closer to the closed end. The radiative heat flux could be minimized if the stack is short, the pores size smaller with the stack positioned closer to the closed end. To decrease the conductive heat flux, the stack has to be large, the pores size larger and the stack positioned closer to the closed end. The study reports a common norm, which is the stack being close to the pressure anti-node for optimum acoustic power. It appears that longer stack exhibits a higher temperature difference and that smaller pore sizes are preferable when the length of the stack is relatively short. The highest recorded sound pressure level in this study was 112dB.

II. Motivations

The ease in construction, maintenance and cost drives this study to explore a different geometric configuration of a simple SWTAE as the previous studies have. This experimental research reports on the geometric configuration of a simple standing wave thermo-acoustic engine, assessing the average time it takes for models of this kind to produces a sound wave and the minimum offset temperature difference at that minimum time. Moreover, this experimental research aims to assess the reached sound level for the time the experiment is being ran (Approximately 11 minutes in three iterations of three different heat supplied to the engine via cartridge heaters as reported).

This is to assess the magnitude of the sound waves the engine produces and to have a clear understanding of the magnitude of the sound that will be supplied to the traveling wave thermo-acoustic refrigerator it intends to supply the produced waves to. Thermo-acoustic engines show positive attributes that are good enough for research to continue working on bringing this technology close to being adopted in industry and for small scale applications. It is not only the aforementioned attributes that attract engineering research to continuously develop the technology with the potential to mitigate issues related to global warming. The fact that the resonator can be made out of PVC and standard metal, makes it simple to begin constructing the device. The heat exchangers and the stack have proven to be complex and may be expensive components to acquire (for complex systems). Because this is a simple system, the heat exchangers can be made out of basic copper or aluminum, whereas the stack can be made out of a stainless steel wire mash, which is cheaper and easy to construct, parallel plate for excellent performance and a honeycomb ceramic material. However, parallel plate stacks are too difficult and too costly to fabricate, especially when the channel size goes down into the spectrum of tens of microns [8]. Due to the required optimal performance and common practice in recent studies, a honeycomb ceramic stack with square pores as a porous structure will be used in this experimental research. The idea behind this research is to assess the performance of the developed thermo-acoustic engine under the developed geometric configuration. The clarity obtained from this research will be useful for the development of a travelling-wave thermo-acoustic refrigerator driven by a simple SWTAE. The performance of the device developed will be assessed through the measurement of the sound pressure level generated, the required heat supplied and the necessary onset temperature.

III. SYSTEM DESIGN AND CONSTRUCTION

A. Resonator

The resonator makes up the housing of the core and the heat exchangers respectively. The material that composes the resonator is expected to be subjected to high temperatures, approximately 600ºC [9]. Due to high temperatures experienced by the resonator, the material must be selected carefully. Standard metal like aluminum, mild steel, and stainless steel have been considered in previous studies [9]. The study [9] reports that out of the three, aluminum is the lightest and the easiest to machine. However it possesses a melting point of 585℃. The thermo-acoustic engine will be subject to high temperatures beyond the melting point of aluminum. Therefore, unfortunately, aluminum will have to fall of the considered metals. Furthermore, the study reported that stainless steel would yield the best operating conditions as the finish of the metal is clean and has the lowest thermal conductivity. While on the other hand, mild steel with a melting point of 1370℃ has an ability withstand internal pressure up to 140 MPa. The disadvantage of mild steel is that it possesses a high thermal conduction 54W/mK, meaning heat will be lost to the metal unless insulation covers the resonator housing. The study further points out that stainless steel is very expensive and unfortunately must be eliminated as a choice. This is the rationale behind the selection of mild steel in this study for the manufacturing of the resonator housing. The melting point characteristic of this metal also allows welding on it, making it suitable for this design because angle flanges made from mild steel will be welded on either end of the square pipe (tube). The flanges are responsible for the mounting, fastening and sealing of the closed end (pressure anti-node) and the open end (velocity anti-node) with their respective lid, allowing the resonator to be air tight. Fig. 5 shows two different views of the resonator built. Details of the geometry of the resonator are provided in Table 1.

Fig. 5. Mild Steel Hollow Square with flanges & sealed resonator, both closed and open end

Table 1: Resonator Specifications.

Resonator Specifications	
Material	Mild Steel
Melting point	1370℃
(b x W)mm (outside)	(70 x 70)mm
Resonator Length (End to End) mm	360mm
Resonator Length (Flange to Flange) mm	260mm
Resonator wall thickness	3mm
Open end round tube (D x l) mm	(60 x 70)mm

B. Stack

There are a number of stacks that can be used in this application; however, availability, cost and their performance are the criterion used to select which is best suited for the current experimental study. Previous studies point out that pin array stack profiles followed by the parallel plates profile perform better, however the machining costs of the pin array profile are very high [9]. Mylar is also considered in other studies as a typical and simple stack; however, the low melting point of 232 ℃ will not be suitable for this application [9]. Honeycomb ceramic substrates (Fig. 6) are readily available at the University and can withstand a temperature of 1600℃. The temperature specifications make it suitable for this application. The honeycomb ceramic stack used in this experimental research has 400 CPSI, with square pores. The honeycomb ceramic stack sits 130mm from the closed end of the engine (pressure anti-node). Table 2 provides a summary of the specifications of the stack considered in this study.

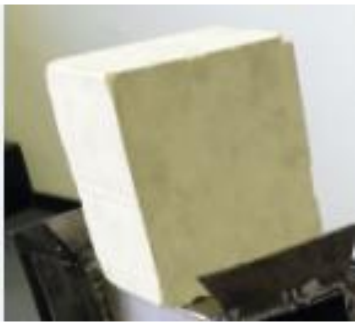

Fig. 4. Honeycomb Ceramic Stack

Table 2. Stack specifications

Stack Specifications	
Type	Honeycomb Ceramic stack
Melting point	1600℃
b x W x L	(95 x 95 x 95)mm
Position	130mm (center of stack to closed end)

C. *Working gas*

The pore sizes have to be large enough in order to minimize the effect of viscosity and small enough in order to improve the heat transfer between the surface of the honeycomb ceramic pores and the gas.

The thermal penetration depth is described as:

$$\delta_K = \sqrt{\frac{2K}{\rho m.\omega.Cp}} \quad (1)$$

Where, K, represent the thermal conductivity and constant pressure respectively.

Viscous penetration depth in Equation (2), describes the thickness where viscosity is predominant. The viscosity effect occurs inside the pores of the stack and is an effect that is not wanted. The higher the viscous penetration depth, the lower the kinetic energy of the moving particles [10]. Viscous penetration depends on the kinematic viscosity v, and the angular frequency ω, of the oscillating fluid particles. The viscous penetration is describes as:

$$\delta_v = \sqrt{\frac{2v}{\omega}} \quad (2)$$

The selection of the working fluid is based on the Prandtl number, known as the ratio between the thermal and viscous penetration depth. A low Prandtl number for the working fluid is preferable. However, based on availability, air is free and therefore it is the used working gas in this experiment at atmospheric pressure.

$$\sigma = \left(\frac{\delta_v}{\delta_K}\right)^2 \quad (3)$$

D. *Heat Exchangers*

Heat exchangers form part of the core in this system. This means that if the heat transfer between the heat exchangers and the face of the stack is not effective, there will be difficulties in reaching the onset temperature difference and the engine will not produce sound. Effective heat exchanging materials are material that have good capacity for heat and can spread heat across the face of the stack effectively. Three materials have been considered in this study, Copper, brass and Aluminum.

Copper can be acquired easily and possesses the required characteristics to maximize heating and cooling on either side of the stack, maximizing chances of an effective heat exchange. With a thermal conductivity of 385 W/m K and a melting point of 780 ºC, copper is best suited for this application and it is the chosen material for the fabrication of heat exchangers, both Hot and Cold based on the comparison summarized in Table 3.

Table 3: Heat Exchanger material specifications

Material	***Thermal Conductivity (W/m K)***
Aluminum	205.0
Brass	79.0
Copper	385.0

Cartridge heaters have been inserted in holes drilled on a multitude of copper strips as shown in Fig. 7. Copper pipes have been inserted in the holes drilled on copper strips considered for the building of the cold heat exchanger. Running water was used for cooling. Hence, copper was used for the distribution of heat/cooling across the surface of the stack. The thickness and the width of the used copper bare for heat exchangers are (t x w) = (5 x 20) mm. The final assembly of the hot and cold heat exchanger is shown in Fig. 8.

Fig. 5. Cold and Hot heat exchanger

Fig. 6. Hot and Cold heat exchanger Assembled into the Resonator

IV. Experimental Setup and Procedure

The main objectives of the experiments conducted in this paper were to obtain:

- The temperature difference across the stack when adjusting the input voltage to the cartridge heaters from 90V to 170V;
- Record the magnitude of the sound pressure level generated for each configuration;
- Record the frequency of the sound generated in each case.

A. Experimental Apparatus

Fig. 9 shows a schematic drawing of the experimental apparatus with the actual experimental setup shown in Fig. 10. Two K-type thermo-couples were positioned each side of the stack in order to record the temperature. A microphone placed coaxially in front of the opened end of the engine was used to record the sound level. The analogue signal collected through sensors of these instruments is then sent to the DAQ instruments which are the data acquisition instruments, both for the sound level meter and the temperature measurement across the stack. The data acquisition hardware (DAQ) is connected to a computer for the visualization, recording and processing of the data. LabVIEW 8 was used as the environment for data visualisation and processing, together with a National Instruments (NI) DAQ hardware (NI USB-928A and NI myDAQ). A portable USB based DAQ is chosen for thermocouple measurement (National instruments hardware NI USB-928). The sound level meter is a portable five digits, compact sized, digital display designed for long term measurements, with an operating environment of 0 to 50 °C. This sound level meter has been connected to the NI myDAQ hardware to compute the Fast-Fourier Transformation (FFT) for analyzing and measuring the signals from DAQ devices. FFTs are computed to evaluate the resonant frequency of thermo-acoustic engine. Prior to the start of the experiment, electric voltage from the AC power supply was set and ultimately used to power the electric cartridge heaters. The cold side was connected to the running water supply, to provide cooling to the cold side of the stack as the other side is heated. Each test was run over 660s (approximately 11 minutes).

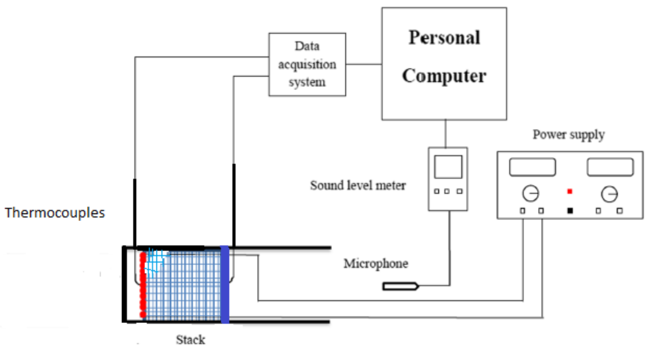

Fig. 9. Schematic drawing of the Experimental setup

Fig. 7: Experimental Setup

B. Experimental Proccedure

Three tests were performed for each configuration. The voltage supply to the cartridge heaters was adjusted from 90V to 170V because of the limitation of the cartridges. Each experiment is runs for approximately 11 minutes (660s). This is to identify the time taken for the onset temperature difference across the stack to be reached. The onset time is the time it takes for the engine to start producing sound. Out of the three iterations, average results has been reported. Prior to every decrement of the experiment, the voltage supply is set to the required power input. Multi-level meter is used to set the voltage to the required voltage input.

V. Results and Discussion

*A. **Evolution of the temperature as a function of time***

The temperature difference (ΔT) across the stack has been recorded after each experiment. Fig. 11 shows the growth of the temperature at the hot heat exchanger (Thot), the drop of the temperature at the cold heat exchanger (Tcold) and the evolution of the temperature difference ΔT. This Figure shows the results obtained after setting the input voltage to 170V. It appears that the temperature become stable after approximately 660 sec which justify the reason why this timing has been adopted for all experiment.

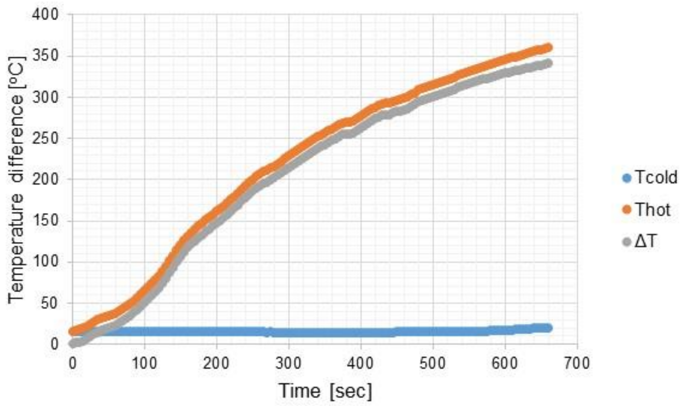

Fig. 11. Temperature difference across the stack

B. Frequency

The frequency of the sound wave has been recorded after each set of experiment. A screenshot showing the results obtained is reported in Fig. 12. This sample corresponds to a voltage of 170V. The frequency is approximately 140 Hz corresponding to the first pic of the FFT signal.

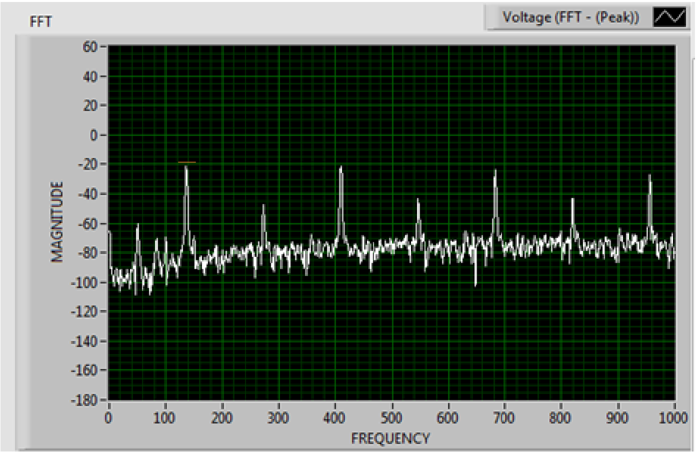

Fig. 12. Frequency spectrum of the sound output

C. Sound levels, onset time and temperature as a function of the voltage supply.

Table 4 provides a summary of results obtained. It gives the average of the successive experiment conducted under the same condition. The trends obtained has been presented in Fig. 13.

Table 4. Table of Results

Results			
Voltage supply (V)	***Sound pressure level (dB)***	***Time taken to produce sound (min:sec)***	***Onset temperature difference (°C)***
170	115.8	5:18	217.87
150	114.5	7:55	220.14
130	110.7	10:25	228.03

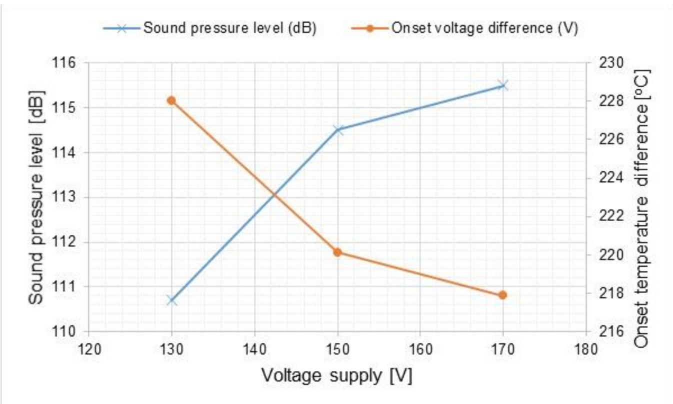

Fig. 13. Sound pressure level and Onset temperature difference as a function of Voltage supply

The minimum temperature difference required to produce a sound was 217.87°C. This corresponds to a voltage supply of 170V with a sound level generated of 115.5 dB (Table 4). In general, the frequency of the sound generated didn't change significantly for all the configuration considered in this study. This frequency was evaluated to be 140 Hz (Fig. 12). It appears that as the voltage supply increases (source of heat), the onset temperature difference drops (Fig. 13). This means that higher sources of heat are more likely to increase the likelihood of sound generation. Interestingly, the supply heat is proportional to the magnitude of the sound generated with a maximum sound level of 115.5 dB as reported in Table 4. One of the interesting finding from this investigation is the relationship between the onset time and the supply voltage. It appears that the higher the supply voltage is, the lower the onset time required to generate a sound wave will be as suggested in Table 4.

In summary:

- The power input is proportional to the voltage supply, into the system;
- The input power is proportional to the sound level produced by the engine. The higher the voltage, the higher the sound level becomes;
- This relationship was also observed with the time it takes to reach the onset temperature difference with respect to the power supply. The lower the power supply, the longer it takes for the engine to start producing sound;
- The cold temperature was maintained below 15°C, thus maintaining the temperature difference across the stack for an effective cycle of sound production. The temperature difference across the stack is critical to the performance of the engine because it determines the sound level (the acoustic power) produced by the engine;
- A constant average frequency of 140Hz was produced, regardless of the change in the power input, in terms of voltage, to the engine;
- The maximum-recorded average sound level produced by the thermo-acoustic engine developed in this study is 115.5 dB corresponding to an onset temperature difference of 217.87°C within an onset time of 5 minutes and 16 seconds.

VI. CONCLUSION

This work presents the development and construction of a thermo-acoustic engine as a promising drive or power supply to a travelling wave thermo-acoustic refrigerator. The simple standing wave thermo-acoustic engine exhibits potential and good attributes as the driver of a thermo-acoustic refrigerator which was the motivation and drive for this development and experimental research. The reported main contributions relate to the details of the geometry of the device and the influence of input parameters namely the source of heat on the magnitude of the sound generated by the engine.

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